Cryo Etched Black Silicon and Applications

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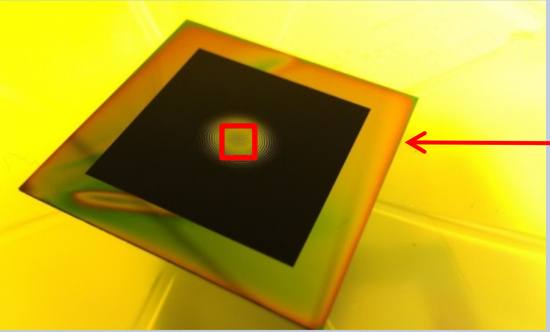
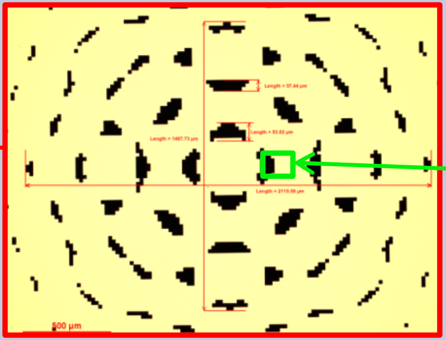
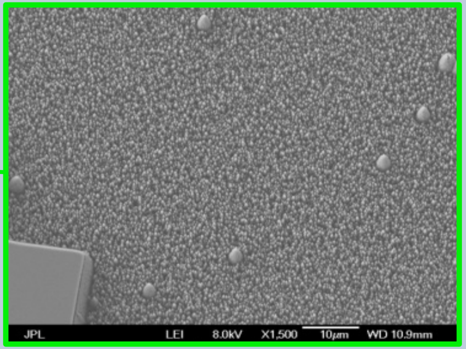
Black Silicon Description

"Black silicon" is a surface texturing of a silicon substrate, resulting in a surface with low reflectivity of visible/IR radiation.





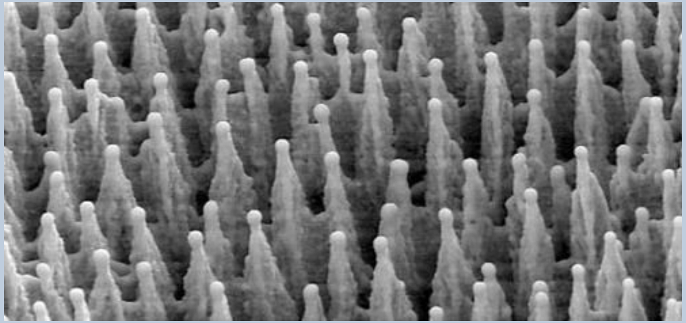


Example: Coronagraph mask with patterned black regions formed by black silicon

Properties

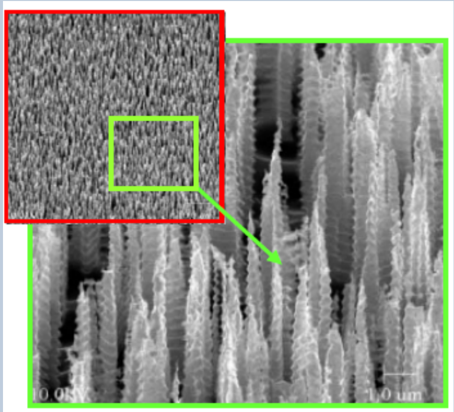
- **Greatly enhanced surface area (applications: capacitors, batteries, gas sensors)**
- **Super hydrophobic surface (can be made hydrophilic with surface coating or oxidation) (applications: fluidic devices, thermal management)**
- **Optically black surface (applications: stray light elimination, high contrast imaging, bolometers, solar cells)**

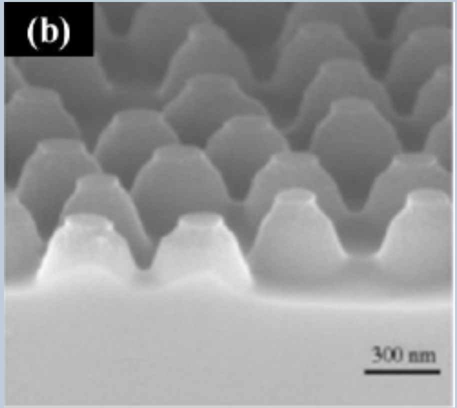
Examples of Black Silicon Formation Techniques



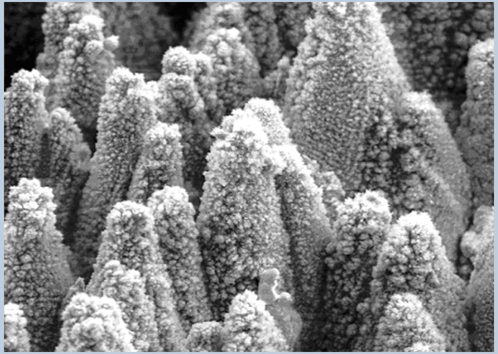
Silicon substrate exposed to high intensity laser pulses in the presence of SF_6 (SiOnyx)

Bosch etch with micro masking produced through over passivation (JPL)





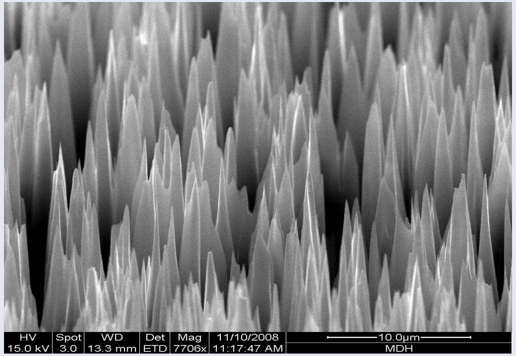
Silicon nanopillars formed by reactive ion etching through a mask of polystyrene spheres (Korea Univ. of Science and Technology)

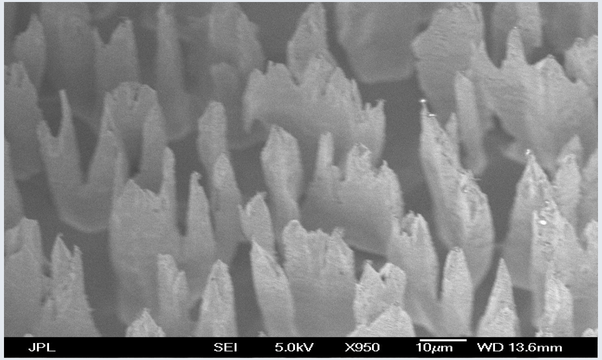


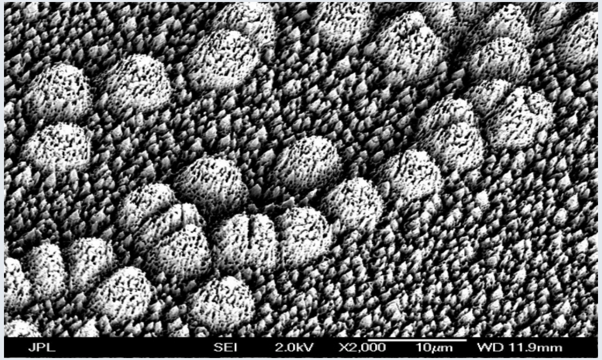
Reactive ion etching of Si in CCl4 and HCl plasmas (General Electric)

Cryo Etched Black Silicon

Formation process: Oxygen combines with SF_6 + Si etch byproducts to form a passivation layer atop the Si when the etch is performed at cryogenic temperatures. Excess flow of oxygen results in micro masking, enabling the formation of black silicon.





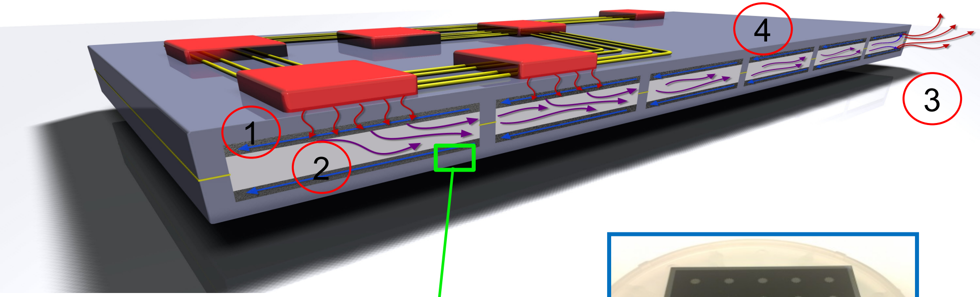


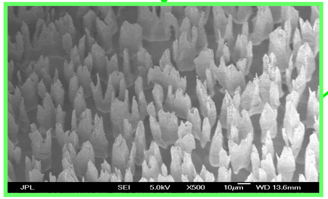
Characteristics of cryo etched black Si:

- **Cryo etch blackening process is rapid and repeatable**
- **Process parameters can be adjusted for control over average height (1 – 150 μm) and spacing of needles**
- **Blackened regions definable with lithographic precision over large areas**
- **Compatible with arbitrary doping level of silicon**
- **Robust, non-outgassing textured surface compatible with wet processing**

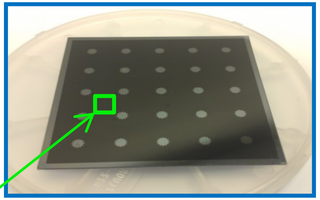
Application: Black silicon wick for heat pipe

1. Heat from high power components conducts through substrate into black Si wick structure
2. Efficient heat transfer occurs from wick into working fluid due to high surface area, causing vaporization of working fluid
3. Vapor condenses in cooler region of heat pipe where the heat can be conducted or radiated away
4. Working fluid is transported back to hot regions due to capillary action, enabled by the small average gap size between needles





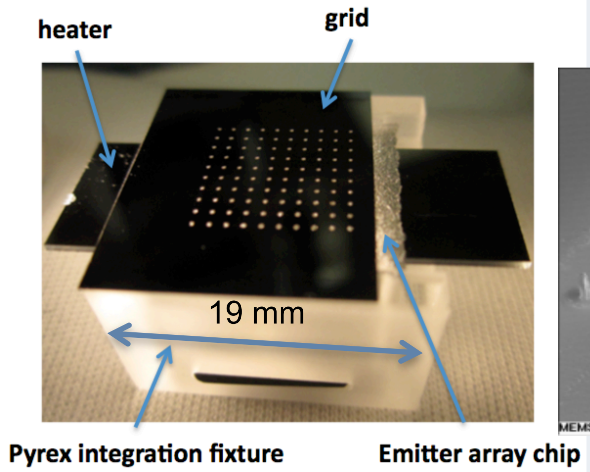
125μm tall black Si wick structure

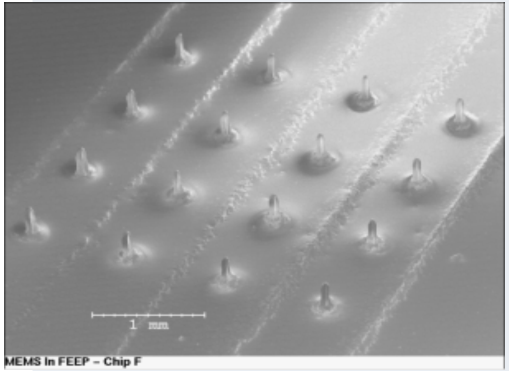


Single sided Si Heat Pipe

Silicon Heat Pipe for thermal management
(K. Yee, E. Sunada, G. Ganapathi, J. Miller, Y. Bae, Dan Berisford)

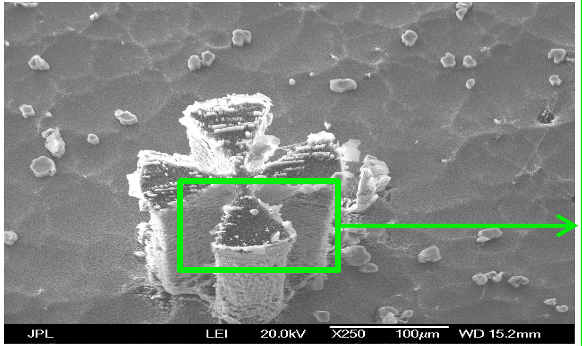
Application: Wicking of liquid metal for ion propulsion

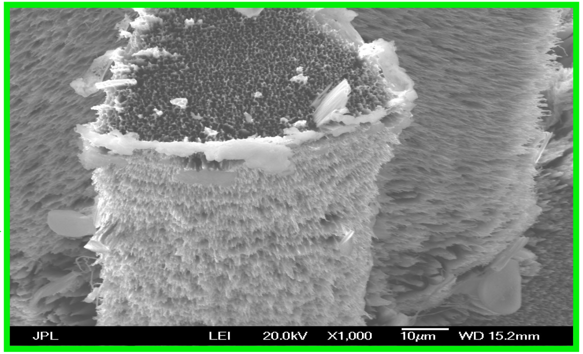


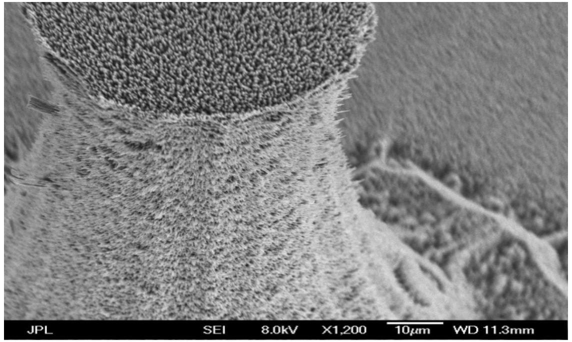


Surface textured ion propulsion emitters for wicking of liquid indium
(C. Marrese-Reading, V. White, K. Yee)

(L) Micro Electric Propulsion (MEP) thruster and (R) micro fabricated emitter array chip

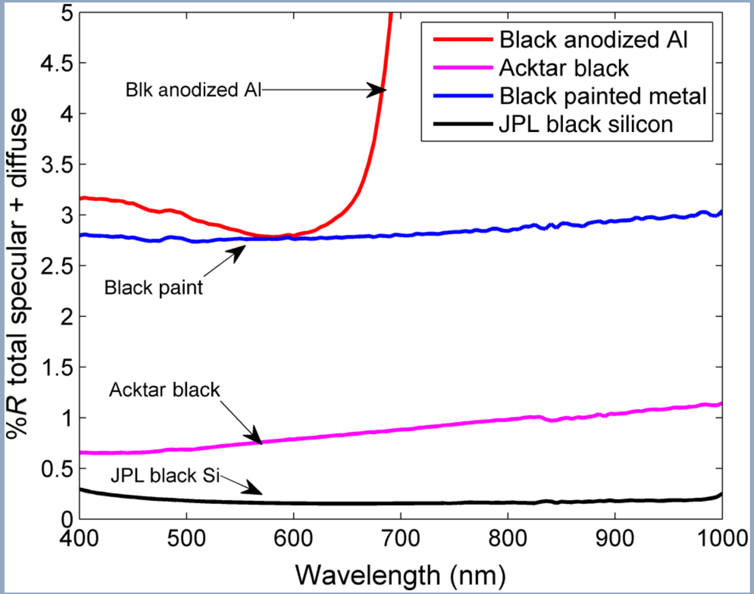




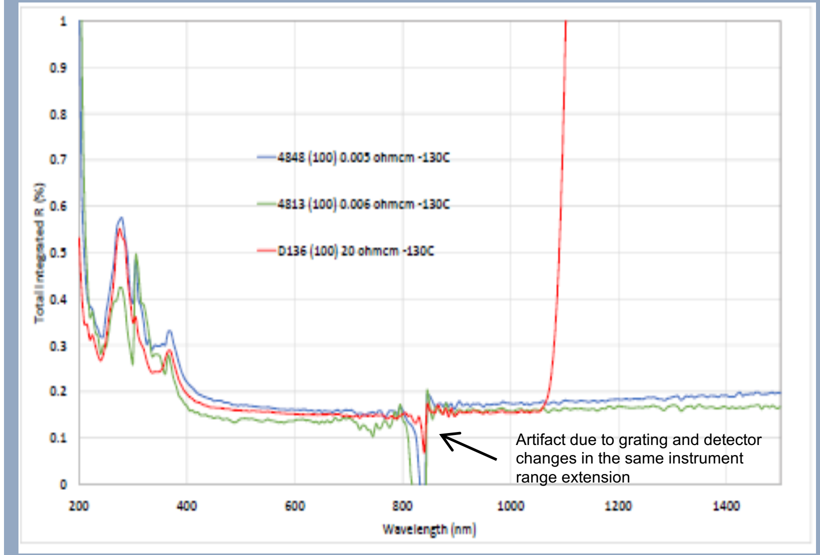


Surface texturing of sidewalls enables wicking of indium to top of emitter

Application: Optical / IR Black



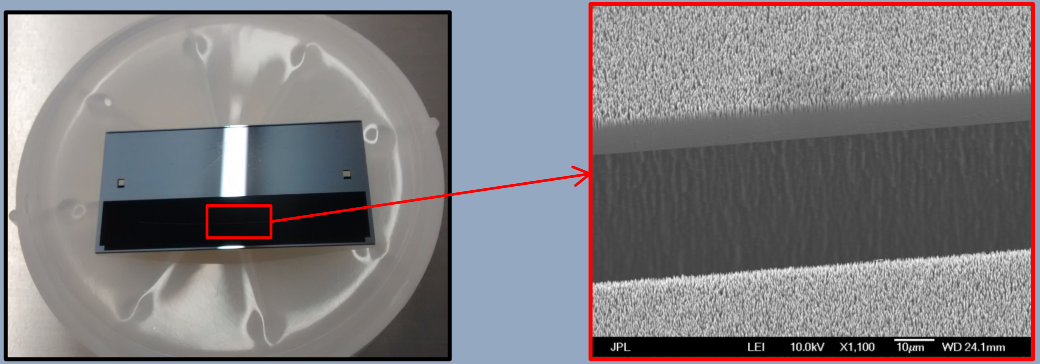
Comparison of measured total integrated reflectance (specular + diffuse) of various materials



Reflectance minimized out to longer wavelengths (>20μm) through use of highly doped silicon

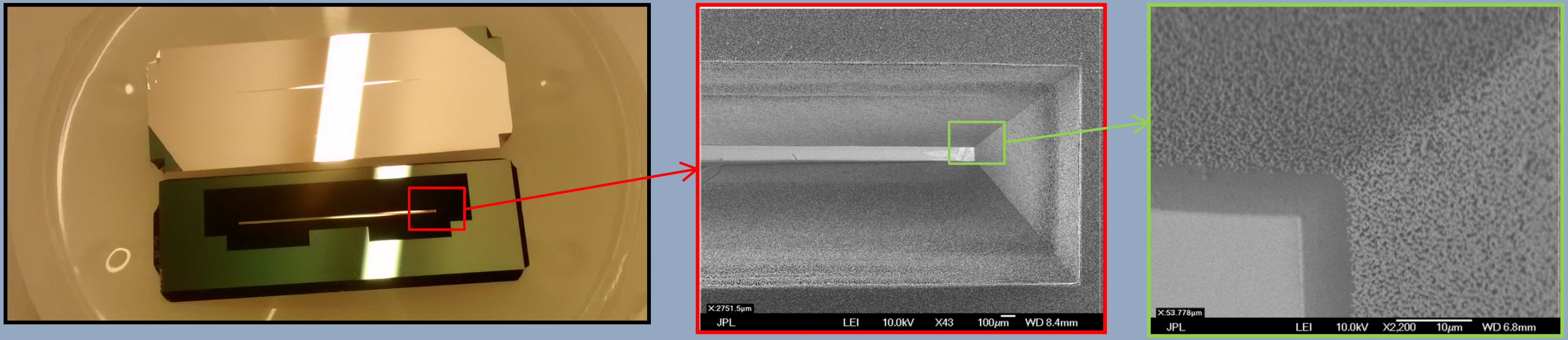
Application: Optical / IR Black

Imaging Spectrometers



Flat geometry slit

Stray light falsely increases the signal at some wavelengths. Black silicon absorption of stray light reduces signal distortion.



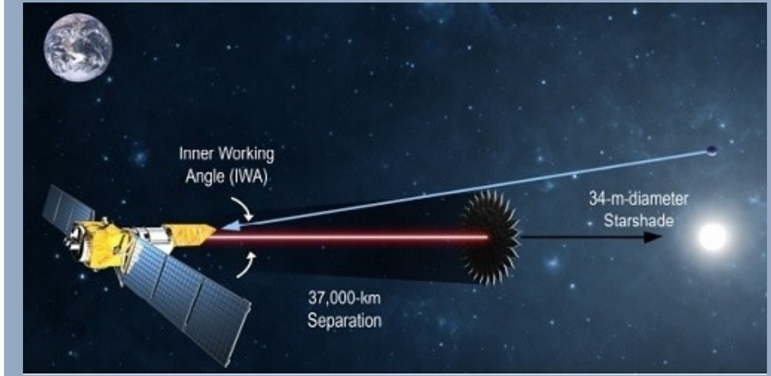
V-groove geometry slit

Application: Optical / IR Black

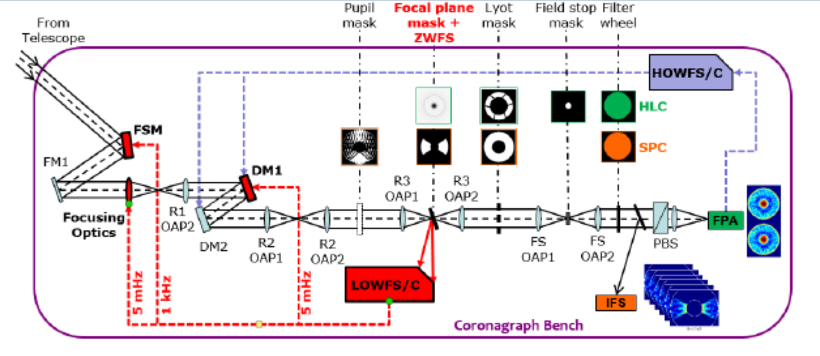
Coronagraph Masks (1)

Imaging an exoplanet requires occultation of the parent star, and suppression of diffracted light from the star:

This can be accomplished with an external occulter (e.g. a Starshade):



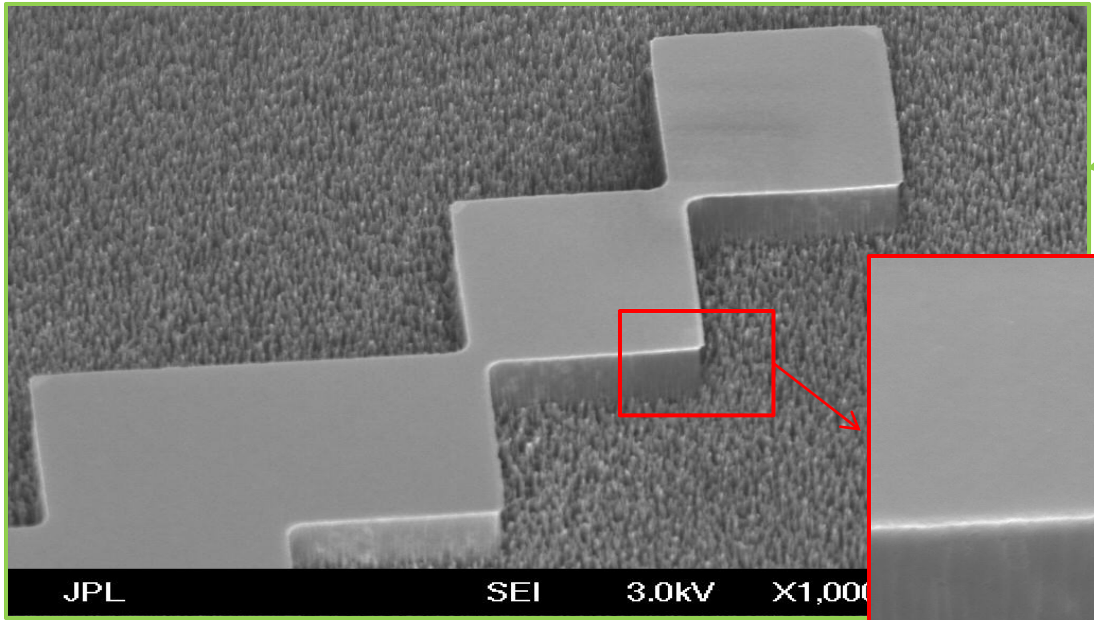
… or with an internal occulter (e.g. a coronagraph):

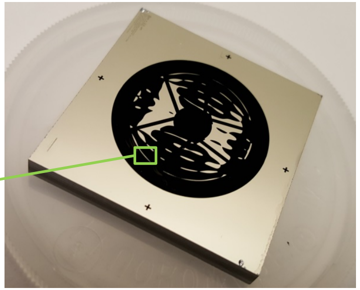


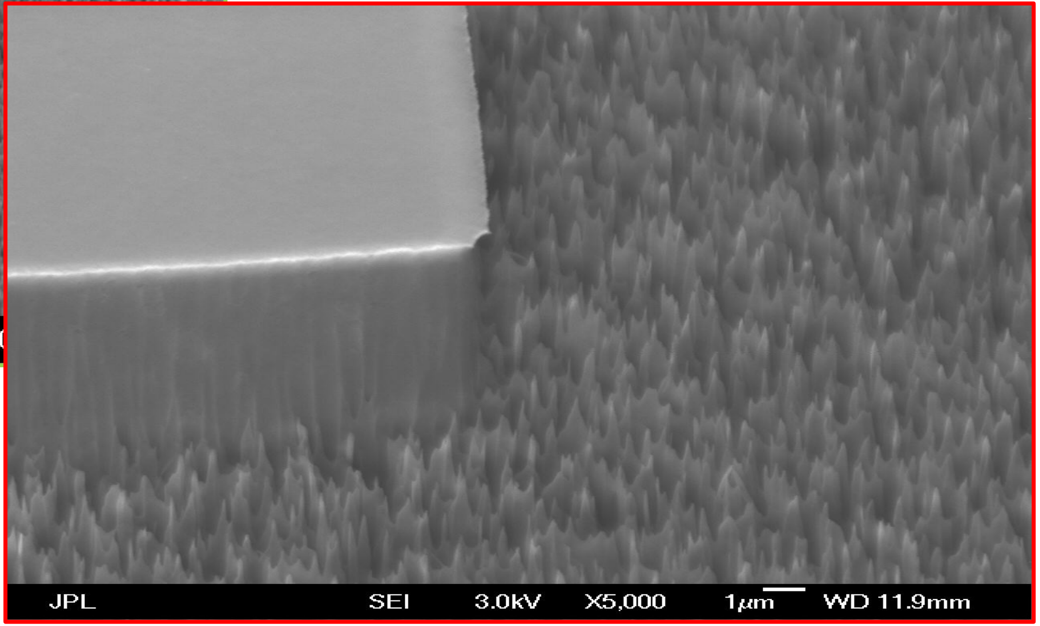
Black silicon is being used for diffracted light absorption on the reflective shaped pupil masks in the Wide-Field Infrared Space Telescope (WFIRST).

Application: Optical / IR Black

Coronagraph Masks (2)



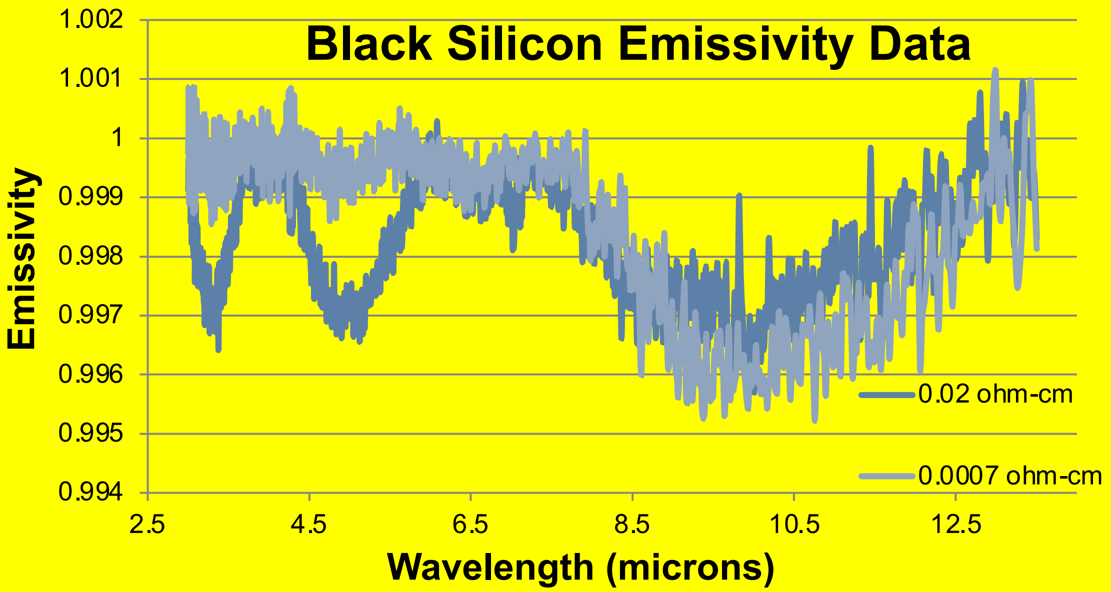




- Micro structured black silicon specular reflectivity: R <10^{-7}
- Diffuse reflectivity: R ~0.1%

Application: High Emissivity Surface

Blackbody Calibration Source



Black silicon emissivity data for samples with two different resistivities .

JPL black Si emissivity comparison with commercial coatings:

Coating type	Emissivity (3-30μm)
JPL black silicon	> 0.995
Acktar Ultra Black	> 0.93
Acktar Fractal Black	> 0.88
Actar Magic Black	> 0.75

Black Silicon blackbody calibration targets will be used on:

- **ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)**
- **CubeSat Infrared Atmospheric Sounder (CIRAS)**

Conclusions

- Devices utilizing black silicon are a continuing, active area of research at JPL
- Some of the properties of black silicon being utilized include:
    - Low reflectivity
    - High emissivity
    - Surface area enhancement
    - Super hydrophobicity / super hydrophilicity
- Flight instruments incorporating black silicon devices include: WFIRST, ECOSTRESS, CIRAS, HyTES, AVIRIS, UCIS, HyspIRI, MaRS2, PRISM, NEON, SWIS
- Acknowledgements: Bala K.Balasubramanian and Victor White. This work was funded by NASA